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Study of CMEs associated intense geomagnetic storms observed during solar maximum 1989-1991

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Abstract . We have analyzed the set of 50 intense geomagnetic storms associated with D_{st} decrease of more than 100 nT, observed during solar maximum period (1989-1991) of solar cycle 22 We have compile these selected intense geomagnetic storm events and find out their association with coronal mass ejections (CMEs) We have found that 80% intense geomagnetic storms associated with coronal mass ejections Two geomagnetic storm events observed during 25/04/89-01/05/89 and 08/07/91 12/07/91, described in detail We concluded that different phases of geomagnetic storms are closely correlated with interplanetary parameters Two kinds of geomagnetic storms known as sudden commencement storm and gradual commencement storm and different storm time changing phenomena have been discussed

Keywords Coronal mass ejections, geomagnetic storms, solar maximum

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1. Introduction

A geomagnetic storm is a global disturbance of earth's magnetic field [1], and usually occurs in response to abnormal conditions in the interplanetary magnetic field (IMF) and solar wind. Geomagnetic storms can be distinguished into two kinds, termed as sudden commencement storm and gradual commencement storm. These kinds of storms are originated from two kinds of solar wind streams [2]. Dungey [3] first proposed that the geomagnetic activities are controlled largely by north-south component of the IMF by the process known as magnetic reconnection. The north-south component of the IMF, which is antiparallel to the dipole field of the earth will initiate reconnection between the two fields, allowing the efficient transfer of mass, momentum and energy from the solar wind into the magnetosphere, which causes geomagnetic storms, sudden ionospheric disturbances (SID's) and ground-level enhancement (GLE) on the earth.

There are many controversies about solar origin of interplanetary shocks and geomagnetic storms. About 4-5 decade ago, it is believed that large solar flares were responsible for interplanetary shocks and intense geomagnetic storms. Joselyn and McIntosh [4] have shown that the solar disappearing filaments have also been linked with geomagnetic storms and interplanetary disturbances (IPDs). Many recent studies and Skylab observations show that active sunspot regions, coronal mass ejections, eruptive prominences and disappearing filaments are the active energy emitting regions and they produce large interplanetary disturbances and intense geomagnetic storms. About two decades ago large coronal eruptions, now known as coronal mass ejections, were discovered in coronagraph observations on the OSO-7 [5] and Skylab [6] spacecraft's. The CMEs are vast structure of solar plasma and magnetic fields, which are expelled from the Sun into the heliosphere and make a prime link between solar and geomagnetic activities. The correlation of CMEs and intense geomagnetic storms have been discussed for different periods by several authors [7-11]. Intense geomagnetic storms are often associated with CMEs and/or interplanetary shocks in the solar wind resulting from interaction between high-speed and low-speed plasma streams [12]. The occurrence of intense geomagnetic storms varies with maximum and minimum phases of 11-year sunspot cycle. Maximum numbers of intense geomagnetic storms were occurred during solar maximum period, whereas, few numbers of intense geomagnetic storms were observed during solar minimum. During solar maximum, maximum numbers of large geomagnetic storms were caused by transient disturbances in solar wind, which are originated by coronal mass ejections. Near solar minimum, maximum numbers of large geomagnetic storms were associated with corotating solar wind streams arising from coronal holes. So, here a question arises what is correlation between intense geomagnetic storms with coronal mass ejections during solar maximum period Considering previous work on correlation between intense geomagnetic storms with CMEs, we have examine the association of intense geomagnetic storms with CMEs for solar maximum period (1989-91) of solar cycle 22. From two case histories, we have discussed the association of intense geomagnetic storms with different interplanetary parameters, are shown graphically.

2. Data set and analysis

In the present analysis, we have sorted out large geomagnetic storms associated with D_{st} decrease of more than 100 nT, IMF $B \geq 10$ nT with time duration greater than 3 hours, during the solar maximum period (1989-91). The selected 50 intense geomagnetic storm events are listed in Table 1. The data of equatorial D_{st} values and mass ejection from Sun have been compiled from various volumes of Solar Geophysical Data bulletins issued by U. S. Department of commerce, NOAA. The different interplanetary parameters, *i.e.* solar wind velocity, interplanetary magnetic field (IMF B) and north-south component of interplanetary magnetic field (IMF B_z) data measured through a number of spacecraft's/satellites have been compiled and reported for different periods by King [13]. In Table 1 first and second column contain the serial number and date of observed storm respectively. The third column presents the magnitude of storm in nT. The fourth column represents the onset data/time of main phase. The SSC's time is denoted in column fifth. Two kinds of geomagnetic storms are given in sixth column. In this column, sudden commencement storm and gradual commencement storm are denoted by S and G. The association of intense geomagnetic storm with CMEs is presented in column number seven. The eighth column presents the associative kind of CMEs events.

Table 1. List of selected 50 intense geomagnetic storm events observed during the solar maximum period (1989-1991), their associative features and association with coronal mass ejections.

S. No	Date of observed storm	Magnitude of storm (nT)	Onset of main phase date/hr.	SSC's time date/hr	Type of storm	Associa-tion with CMEs	Associative CMEs events
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Year-1989							
01	Jan 11	-132	11(18)	–	G	–	–
02	Jan 16	-122	15(08)	–	G	Yes	CME (II)
03	Jan 20	-122	20(15)	20(16)	S	Yes	CME (II & IV)
04	Mar 9	-103	08(21)	08(19)	S	Yes	CME (SP, II & IV)
05	Mar 14	-599	13(02)	–	G	Yes	CME (SP, IV & II)
06	Mar 16	-118	16(09)	–	G	Yes	CME (SP & II)
07	Mar 19	-110	19(06)	–	G	Yes	CME (SP, II & IV)
08	Mar 29	- 131	27(17)	26(24)	S	Yes	CME (IV & II)
09	Apr 14	-105	14(13)	14(10)	S	–	–
10	Apr 26	-132	25(18)	25(11)	S	Yes	CME (S & II)
11	Jun 10	-144	09(01)	08(24)	S	–	-
12	Aug 15	-146	14(08)	14(07)	S	–	–
13	Aug 29	-153	27(20)	27(15)	S	Yes	CME (S & II)
14	Sep 16	-125	15(05)	15(03)	S	Yes	CME (II)
15	Sep 19	-257	18(20)	18(12)	S	Yes	CME (Q, IV & S)
16	Sep 26	-157	26(09)	26(04)	S	Yes	CME (II & S)
17	Oct 21	-270	16(16)	–	S	Yes	CME (S, II & IV)
18	Nov 13	-124	13(01)	-	G	Yes	CME (II)
19	Nov 17	-266	16(18)	–	G	Yes	CME (II)
20	Dec 31	-104	29(10)	29(08)	S	Yes	CME (II)
Year-1990							
21	Mar 12	-159	12(21)	12(16)	S	–	-
22	Mar 21	-133	20(10)	–	G	Yes	CME (II)
23	Mar 25	-116	25(09)	–	G	Yes	CME (II & S)
24	Mar 30	-182	29(10)	–	G	Yes	CME (SP & IV)
25	Apr 10	-278	09(23)	-	G	Yes	CME (II)
26	Apr 12	-172	12(05)	–	G	Yes	CME (IV)
27	Apr 17	-112	17(08)	–	G	Yes	CME (IV)
28	Apr 24	-107	24(06)	–	G	–	-
29	Apr 29	-101	28(02)	–	G	Yes	CME (II)
30	Jun 13	-152	12(11)	12(09)	S	Yes	CME (II & IV)
31	Jul 29	-129	28(11)	27(21)	S	Yes	CME (IV)
32	Aug 26	-116	26(07)	–	G	Yes	CME (IV & II)
33	Oct 10	- 133	09(19)	08(18)	S	–	–
34	Nov 27	-136	27(16)	27(10)	S	Yes	CME (II)

Table 1 (Cont'd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Year-1991							
35	Mar 25	-298	24(06)	24(03)	S	..Yes	CME (IV)
36	May 19	-103	17(02)	16(21)	S	Yes	CME (IV & Q)
37	Jun 5	-219	04(19)	04(15)	S	Yes	CME (IV)
38	Jun 10	-131	10(07)	–	G	Yes	CME (IV & II)
39	Jun 11	-138	10(20)	--	G	Yes	CME (II & S)
40	Jun 13	-108	13(09)	13(08)	S	Yes	CME (IV & II)
41	Jul 9	-198	08(20)	08(18)	S	Yes	CME (IV & II)
42	Jul 13	-185	13(21)	12(20)	S	Yes	CME (II & IV)
43	Aug 2	-113	01(16)	–	G	–	–
44	Aug 19	-170	19(01)	18(23)	S	–	–
45	Aug 30	-111	30(06)		G	Yes	CME (IV)
46	Oct 2	-162	01(19)	–	G	Yes	CME (IV)
47	Oct 29	-251	28(12)	–	G	Yes	CME (II & IV)
48	Nov 9	-354	08(13)	08(12)	S	–	–
49	Nov 19	-123	18(22)		G	Yes	CME (II)
50	Nov 22	-137	21(03)	–	G	Yes	CME (II & IV)

Kind of events

CME (II)-CMEs associated with type-2 radio burst

CME (IV)-CMEs associated with type-4 radio burst

CME (SP)-CMEs associated with flare spray

CME (S)-CMEs associated with flare surge

CME (Q)-CMEs associated with quiescent prominences

Types of storm

S-Sudden commencement storm

G-Gradual commencement storm

3. Results and discussion

The summarized results of table 1 are given following.

• Total number of intense geomagnetic storms	–	50
• Total number of sudden commencement storms	25	50%
• Total number of gradual commencement storms	25	50%
• Total number of intense storms associated with SSC's	25	50%
• Total number of intense storms associated with CMEs	40	80%
• Total number of intense storms associated with CMEs type-II radio-bursts	18	45%
• Total number of intense storms associated with CMEs type-IV radio-bursts	13	32.5%
• Total number of intense storms associated with CMEs flare spray	05	12.5%
• Total number of intense storms associated with CMEs flare surge	03	7.5%
• Total number of intense storms associated with CMEs quiescent prominences	01	2.5%

The solar cycle 22 is exceptional among all other 21 solar cycles, containing two peaks during the year 1989 and 1991. So, we have taken the period (1989-91) as solar maximum period of solar cycle 22. From above mentioned results, out of selected 50 intense storm events 25 are sudden commencement type and rest 25 are gradual commencement type. From this result, we have find same occurrence rate for sudden and gradual commencement types of storm for solar maximum period of solar cycle 22. So, we can conclude that the occurrence of sudden and gradual commencement types of storm does not vary with 11-year sunspot cycles. The onset time of geomagnetic storms is generally coincident with the time of SSC's [14], through it is not always essential. Zhu and Wada [15] observed that the D_{st} value is minimum nearly 10 to 20 hours after the occurrence of S.S.C's. Moreover, there are number of SSC's that are not found to be associated with any significant change in the D_{st} magnitude. In our selected study period 50% intense geomagnetic storms were associated with SSC's. It is also seems that in most of the cases the onset of main phase just follows the SSC's. The most probable time difference between SSC's and onset of main phase lies between 1-6 hours for 76% SSC's associated intense geomagnetic storms. It also seems that the storm associated with SSC's shows faster recovery in comparison to other storms that is not associated with SSC's.

During the aforesaid period 80% intense geomagnetic storms were associated with CMEs. These results indicate that the majority of intense geomagnetic storms were associated with CMEs during solar maximum period of solar cycle 22. The associations of CMEs with intense geomagnetic storms have been discussed by several authors [7-11]. Gosling *et al* [12] have shown that all but one of the 37 largest geomagnetic storms in 1978-82 were associated with earth passage of either shock disturbances or CMEs or both. Our present study results are approximately as similar as the previous findings have been discussed so far by many authors for different periods. According to many recent studies, CMEs can be associated with three types of solar activity, *viz.*, H-alpha solar flares, eruptive prominences and X-ray bursts. The Skylab and SMM mission show that about 40% CMEs were associated with type-II and only 5% were associated with type-IV radio- bursts. We have found that sometimes CMEs may be associated with more than one solar activity. In eighth column of Table 1, we can see that a CME have been associated with flare spray, flare surge, prominences, type-II and/or type-IV radio-bursts. Generally type-II and type-IV radio-bursts are most affective for producing strong interplanetary shocks, which cause intense geomagnetic storm on the earth. Our observations show out of the intense geomagnetic storms 45% could be attributed to type-II radio-bursts and 32% to type-IV radio-bursts. These results indicate the intense geomagnetic storms are generally associated with CMEs during solar maximum. The CMEs associated intense geomagnetic storms are mostly associated with either type-II or type-IV radio-bursts in comparison to other solar activities, *e.g.*, solar flares, prominences and type-III radio-bursts.

For better understanding of the association of intense geomagnetic storms with CMEs type-II and type-IV radio-bursts, and different interplanetary parameters, we have analyzed two intense geomagnetic storm events observed during 25/4/89-1/5/89 and 8/7/91-12/7/91. The detail analysis of these storm events described as follows :

Event I (Intense geomagnetic storm event observed during 25/4/89-1/5/89) :

The intense geomagnetic storm event is sudden commencement type associated with type-II radio-bursts. This storm having peak magnitude -132 nT, initial phase duration -07 hours, main phase duration -13 hours and recovery phase duration -130 hours. The association of above mentioned geomagnetic storm with different interplanetary parameters, are plotted in Figure 1. During the main phase of this storm solar wind speed and IMF magnitude peaking around 661

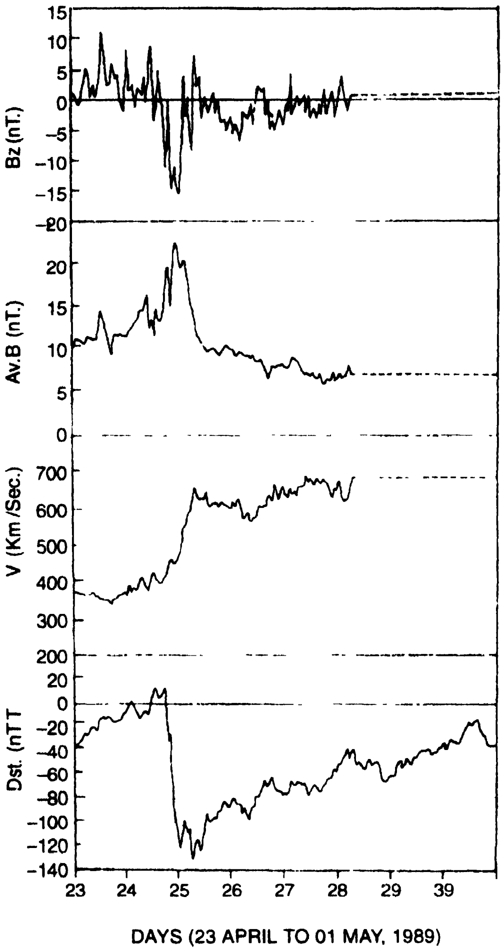

Figure 1. Shows the association of geomagnetic storm with solar wind speed, interplanetary magnetic field IMF B and IMF B_z observed during 25/4/89 to 1/5/89 (Dashed line ----- shows the data gap)

Table 2. List of various solar events observed during April 22-29, 1989

S No	Dates	Time (UT)	Duration	Associated solar events
01	22/4/89	03.47	04 min	CME (type-II)
02	22/4/89	06·00	05 min	CME (type-II)
03	22/4/89	06.55	18 min	CME (flare surge)
04	22/4/89	08 23	05 min	Solar flare (Imp. -1B)
05	23/4/89	07.20	40 min.	CME (flare surge)
06	23/4/89	08:35	105 min.	CME (flare surge)
07	23/4/89	21.55	01 min	CME (type-II)
08	23/4/89	23:55	49 min.	Solar flare (Imp. - IB)
09	23/4/89	08·48	47 min.	CME (flare surge)
10	23/4/89	07:18	17 min.	CME (flare surge)

km/s and 22.5 nT respectively. The northward IMFB$_z$ turned its value from 4.8 to – 11.6 before onset of main phase. The solar origin of this storm is CMEs type-II radio-bursts that occurred during (03:47 – 03:51 and 06:00 – 06:05 UT) at 22/4/89. Many solar events occurring one after the other during 22/4/89 – 29/4/89, are listed in Table 2. This has a long longevity and many small peaks.

Event 2 (Intense geomagnetic storm event observed during 8/7/91–12/7/91) :

This intense geomagnetic storm event is also sudden commencement type associated with type-IV radio-bursts. This storm having peak magnitude -198 nt, initial phase duration -02 hours, main phase duration - 19 hours and recovery phase duration – 198 hours. The association of above mentioned intense geomagnetic storm with different interplanetary parameters, are shown in Figure 2. During the main phase of this storm, solar wind velocity and IMF magnitude peaking around 747 km/s and 32.5 nT respectively. The northward IMF B$_z$ turned its value from 9.5 to –12.2 before onset of main phase. The solar origin of this storm is CMEs type-IV radio-bursts that occurred during (10:02 – 10:12 UT) at 5/7/91. The different solar activities that takes

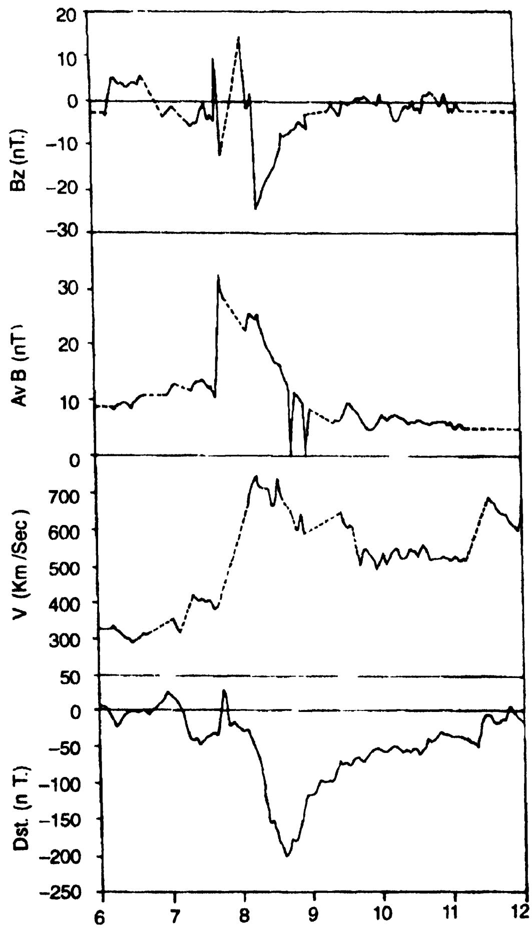

Figure 2. Shows the association of geomagnetic storm with solar wind speed, interplanetary magnetic field IMF B and IMF B$_z$ observed during 8/7/91 to 12/7/91 (Dashed line ------ shows the data gap).

place on solar surface during 5/7/91–6/7/91. There are no more solar activities occurs during this storm event, so this storm having one peak.

Table 3. List of various solar events observed during July 05-06, 1991.

S. No	Dates	Time (UT)	Duration	Associated solar events
01	5/7/91	05:00	38 min	Solar flare (Imp. – 1B)
02	5/7/91	08:35	108 min.	Solar flare (Imp. – 2B)
03	5/7/91	10:02	10 min.	CME (type-IV)
04	6/7/91	08.36	204 min	Solar flare (Imp. – 1B)
05	6/7/91	17:37	37 min.	Solar flare (Imp – 2B)

From two case studies following conclusions are drawn :

(i) The initial phase of geomagnetic storm starts when IMF B has low magnitude and IMF B_z is initially northward.

(ii) Main phase of geomagnetic storm starts after increasing in IMF B magnitude and solar wind speed, and turning of IMF B_z from northward to southward.

(iii) The magnitude of this storm peaks 9 hours later after the IMF peak for event 1 During large recovery phase duration (130 hours) of this storm. IMF B magnitude show decreasing trend while solar wind speed shows increasing trend. The large southward IMF B_z is present during recovery phase. We conclude that the large solar wind velocities in the presence of even moderate southward IMF B_z, can extend the recovery phase of the storm to around 130 hours by maintaining the D_{st} values as high as -60 nT. This would not have been possible in the presence of northward IMF B_z, inspite of high solar wind velocities. We can explain this result by event 2, which is shown in Figure 2. This storm is similar to the previous case, but has presence of large northward directed IMF B_z during recovery phase. During recovery phase of this storm comparatively higher magnitude (–198 nT) in comparison as in the previous case recovered within 69 hours in the presence of higher solar wind velocity.

Many recent studies have shown that the magnitudes and different phases of geomagnetic storm depend upon solar wind speed, IMF magnitude and presence of large southward IMF B_z. The geomagnetic activity is generally represented by electromagnetic coupling, V × B, where V is the velocity of solar wind streams and B is the IMF magnitude. The southward IMF B_z provides an opportunity to make strong magnetic reconnection between IMF and earth's magnetic field. When the IMF has large magnitude (≥ 10 nT) and a large southward component, the amount of transferred energy become very large. On the other hand, the transferred energy becomes very small when the IMF is directed preliminary northward. The energy transfer efficiency is of the order of 10% during intense magnetic storms [16]. Viscous interaction, the other prime energy transfer mechanism proposed, has been shown to be only < 1% efficient during intense northward directed IMFs. Tsurutani *et al* [17] have examined the interplanetary and solar cause of five largest geomagnetic storms during the period 1971-86 and found that the extreme value of the southward IMF B_z, rather than the solar wind speeds, are the primary causes of great magnetic storms. So the presence of large southward IMF B_z during higher solar wind velocities can produce large geomagnetic storms, it can extend the recovery phase of the storm and *vice versa.*

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